IF FREQUENCY RESPONSE CHARACTERIZATION EMPLOYING OVERLAPPING FREQUENCY BANDS

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BACKGROUND

1. Technical Field

5   The invention relates to radio frequency (RF) receiver systems and measurements performed on same.

2. Description of Related Art

A frequency response of a radio frequency (RF) receiver or receiving system often is measured or characterized by applying an RF input signal $R(f)$ to an input of

10   the receiver and measuring an intermediate frequency (IF) output signal $I(f)$ produced by the receiver at an IF output. The frequency response or transfer function is a complex ratio of output signal $I(f)$ over the input signal $R(f)$ as a function of frequency f. Moreover, since in most such RF receiver systems an IF portion of the receiver tends to dominate the overall transfer function of the system, the measured frequency

15   response is essentially an IF frequency response of the receiver and may be, in general, represented by a 'filter-like' transfer function $H_f(f)$. Thus, a frequency response measurement of the receiver system is often essentially an IF frequency response measurement or IF characterization of the receiver system.

Typical approaches to receiver system measurement generally assume that the

20   input signal $R(f)$ is known exactly or at least with sufficiently high precision to support a particular error budget for the measurement. Unfortunately however, in many practical situations complete or precise knowledge of the input signal $R(f)$ may be lacking. This is especially true when attempting to perform highly precise characterizations of downconverting receivers such as a modern measurement

25   receiver or a vector spectrum analyzer. Errors or uncertainties in knowledge of the input signal $R(f)$ contribute to an overall measurement error in the receiver transfer function.

Accordingly, it would be advantageous to have an IF frequency response characterization for an RF receiver that compensates for or effectively reduces an

effect that an uncertainty in knowledge of the input signal $R(f)$ has on the characterization. Such an IF frequency response characterization would solve a long-standing need in the area of RF receiver measurement.

BRIEF SUMMARY

5   In some embodiments of the invention, a method of characterizing an intermediate frequency (IF) response of a receiver using measurements performed on overlapping frequency bands is provided. The method employs the overlapping frequency band measurements to reduce or minimize an effect of uncertainties in knowledge of an RF stimulus signal. The method comprises measuring an IF

10   response of the receiver, computing a set of conversion coefficients from the measured IF response, and determining an estimate of an actual IF frequency response using the measured IF response and the conversion coefficients. The method may optionally further comprise removing a radio frequency (RF) tilt introduced by an RF portion of the receiver.

15   In other embodiments of the invention, an IF measurement system that employs measurements of overlapping frequency bands is provided. The IF measurement system comprises a signal generator that applies an RF stimulus signal to the receiver under test, an IF processor that receives and digitizes an IF response of the receiver under test, and a controller that controls the signal generator, receiver under test, and

20   IF processor as well as processing the digitized IF response. The IF measurement system further comprises a computer program executed by the controller that determines an estimate of an actual IF response of the receiver from the overlapping frequency band measurements such that the estimate minimizes an effect of uncertainties in knowledge of an RF stimulus signal.

25   Certain embodiments of the present invention have other features in addition to and in lieu of the features described hereinabove. These and other features of embodiments of the invention are detailed below with reference to the following drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

30   The various features of embodiments of the present invention may be more readily understood with reference to the following detailed description taken in

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conjunction with the accompanying drawings, where like reference numerals designate like structural elements, and in which:

Figure 1 illustrates a simplified block diagram of an exemplary transmitter and receiver portion of an IF measurement system according to an embodiment of the present invention.

Figure 2 illustrates a flow chart of a method of characterizing an IF frequency response of a receiver using measurements of overlapping frequency bands according to an embodiment of the present invention.

Figure 3 illustrates graphical plots of an example set of measurements plotted as a function of RF frequency for a plurality of overlapping bands according to an embodiment of the present invention.

Figure 4 illustrates a block diagram of an IF measurement system according to an embodiment of the present invention.

DETAILED DESCRIPTION

Various embodiments of present invention facilitate measuring or characterizing an intermediate frequency (IF) transfer function or frequency throughput response (hereinafter 'IF response') of a receiver by reducing errors associated with uncertainties in knowledge (hereinafter 'stimulus uncertainties') of a radio frequency (RF) stimulus signal $R(f)$ used to perform the characterization. In some embodiments, such errors associated with stimulus uncertainties may be minimized. Stimulus uncertainties may be a result of an uncertainty associated with knowledge of a baseband transmitter filter frequency response $H_g(f)$ and/or uncertainty in knowledge of a spectrum of a baseband stimulus signal $S(f)$. Additionally, an effect of uncertainty in knowledge of an RF portion of one or both of the transmitter and the receiver similarly may contribute to the uncertainties in the RF stimulus signal $R(f)$ knowledge (i.e., 'stimulus uncertainties').

Figure 1 illustrates a block diagram of an exemplary transmitter and receiver portion of an IF measurement system 1 according to an embodiment of the present invention. The transmitter and receiver portion of the IF measurement system 1 comprises an exemplary radio frequency (RF) signal source or transmitter 10 and an exemplary receiver 20. The IF measurement system 1 produces measurements of an

IF frequency transfer or response characteristic $I(f)$ of the exemplary receiver 20. The measurements are produced using an RF stimulus signal $R(f)$ created by the transmitter 10.

5   As illustrated in Figure 1, the exemplary transmitter 10 comprises a signal generator or baseband stimulus source 12, a transmitter baseband filter 14, an upconverter 16, and a transmitter RF filter 18. The baseband stimulus 12 produces a baseband stimulus signal $S(f)$. The stimulus signal $S(f)$ passes through and is filtered by the baseband filter 14 having a transfer function $H_g(f)$. A filtered baseband signal $G(f)$ is produced at an output of the baseband filter 14. The filtered baseband signal

10    $G(f)$ is upconverted to an RF signal having an RF frequency by the upconverter 16. The upconverter 16 includes a tunable local oscillator (LO), a tuning of which determines the carrier frequency of the RF signal. The RF signal then passes through and is filtered by the transmitter RF filter 18 to produce an RF stimulus signal $R_{tx}(f)$ at an output of the transmitter 10. The RF stimulus signal $R_{tx}(f)$ is then applied to an

15   input of the receiver 20 to perform an IF frequency response characterization of the exemplary receiver 20. The RF stimulus signal $R_{tx}(f)$ is illustrated in Figure 1 as $R(f)$, for the reason set forth below.

The receiver 20 comprises a receiver RF filter 22, a receiver downconverter 24, and an IF stage represented herein by an IF filter 26. The RF stimulus signal $R_{tx}(f)$ is

20   filtered by the RF filter 22 to produce a filtered RF signal $R(f)$. The filtered RF signal $R(f)$ is then applied to and downcoverted to an IF frequency by the downconverter 24. An IF output of the downconverter 24 is applied to and filtered by the IF filter 26 to produce an IF signal $I(f)$ at an output of the receiver 20. The IF signal $I(f)$ is sampled or measured to determine or characterize an IF response of the receiver 20.

25   As used herein, a variable that is denoted as a function of frequency (e.g., $R(f)$ or $H_g(f)$) is a frequency domain or spectral representation of the variable. The variable may represent one or both of a magnitude and a phase or equivalently, a real part and an imaginary part of the variable represented in the frequency domain. Similarly, a variable denoted as a function of time (e.g., $s(t)$) is understood to be a time domain or

30   impulse representation of the variable.

Also, while technically the RF stimulus signal $R_{tx}(f)$ differs from the filtered RF signal $R(f)$ as a result of the action of the RF filter 22, from the standpoint of IF

response characterization, the RF stimulus signal $R_{tx}(f)$ and the filtered RF signal $R(f)$ are similar signals. Therefore, herein no distinction will be made between the RF stimulus signal $R_{tx}(f)$ and the filtered RF signal $R(f)$ (i.e., $R(f)$ will be used) unless the distinction is considered warranted.

The exemplary transmitter and receiver portion of the IF measurement system 1 illustrated in Figure 1 is provided for discussion purposes only and is not meant to limit the scope of any embodiment of the present invention in any way. The exemplary transmitter and receiver portion of the IF measurement system 1 illustrated in Figure 1 is merely representative of essentially any transmitter and receiver portion of an IF measurement system. Specifically, other such transmitter and receiver portions may include elements in addition to or that differ from those illustrated in Figure 1 and still be within the scope of the present invention.

For example, the exemplary upconverting transmitter 10 illustrated in Figure 1 may be replaced by an RF signal generator 10 that directly generates the RF stimulus signal $R(f)$ rather than generating the base band stimulus signal $S(f)$ and then upconverting the baseband stimulus signal $S(f)$ to produce the RF stimulus signal $R(f)$. In another example, a multi-stage upconverting RF signal generator 10 may be employed. In yet another example, the single stage receiver 20 illustrated in Figure 1 may be replaced by a multi-stage downconverting receiver 20. In another example, the receiver 20 may have both upconverting and downconverting stages. Notwithstanding such variations in the transmitter and receiver portion of the IF measurement system 1, virtually any transmitter and receiver portion of an IF measurement system may be represented by the major building blocks or elements illustrated in Figure 1.

Figure 2 illustrates a flow chart of a method 100 of characterizing an IF frequency response of a receiver using measurements of overlapping frequency bands according to an embodiment of the present invention. Method 100 essentially averages measurements of an IF frequency response of the receiver taken for a plurality of overlapping frequency bands. Averaging the measurements reduces an effect of uncertainties in knowledge of a baseband transmitter filter and/or in knowledge of a baseband stimulus signal. In addition, the method 100 may reduce errors associated with uncertainty in knowledge of a transfer function of an RF

portion of a transmitter and/or a transfer function of an RF portion of the receiver. Hereinafter, any such 'uncertainty in knowledge of' is referred to as 'stimulus uncertainty' or 'stimulus uncertainties' for simplicity of discussion herein. In some embodiments, such effect or such errors associated with stimulus uncertainty may be

5   minimized.

In some embodiments, the method 100 combines response measurements in a select manner to obtain an improved estimate of the frequency response of an IF portion of the receiver. In some of these embodiments, the method 100 combines response measurements in an essentially optimal manner. The improved estimate

10   provides a characterization of the IF portion that more closely represents a true or accurate transfer characteristic than the direct or raw receiver measurements obtained without employing the method 100. Among other things, such an improved or more accurate IF response characterization may be employed to construct a compensating filter for the receiver, for example.

15   The method 100 of characterizing an IF frequency response of a receiver comprises measuring 110 an IF response of the receiver for overlapping RF frequency bands. As used herein, an RF frequency band is a contiguous range or set of RF frequencies spanning from a frequency f_l at a lower band edge of the frequency band to a frequency f_u at an upper band edge of the frequency band. The RF frequency

20   band also has a center frequency f_c midway between the lower band edge frequency f_l and the upper band edge frequency f_u. A difference between the upper band edge frequency f_u and the lower band edge frequency f_l defines a bandwidth BW of the frequency band.

RF signals, or portions thereof, within the RF frequency band are converted to

25   IF signals by the receiver. Thus for example, a frequency component of an RF signal centered at an RF center frequency f_c is converted to a frequency component of an IF signal centered at an IF center frequency $f_{c,IF}$. Simultaneously, frequency components of the RF signal on one or both sides of the RF center frequency f_c within the bandwidth BW of the receiver are similarly converted to frequency components on

30   one or both sides of the IF center frequency $f_{c,IF}$. Selecting a given tuning point of the receiver (i.e., tuning the receiver) determines a particular RF frequency band B with a particular center frequency f_c.

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In most cases, a bandwidth BW of the receiver is set or established by an IF filter of the IF stage having an IF bandwidth BW_{IF}. Occasionally however, an RF filter or RF stage having an RF bandwidth BW_{RF} may set the receiver bandwidth BW. For purposes of discussion herein and not by way of limitation, the bandwidth BW_{RF}

5   of the RF frequency band B will be assumed to be equal to IF bandwidth BW_{IF}. Thus, both the RF bandwidth BW_{RF} and IF bandwidth BW_{IF} will be referred to herein as the receiver bandwidth BW without ambiguity or loss of generality.

Furthermore, for the purposes of discussion hereinbelow, it is assumed that there is a one-to-one correspondence between a particular RF signal frequency component

10   within a given or selected RF band B of the receiver and a particular IF signal frequency component within the IF bandwidth BW_{IF} of the output signal $I(f)$ of the receiver. The specific one-to-one correspondence is determined by a particular frequency conversion plan of the receiver. For example, in one such conversion plan, the RF signal frequency components at the lower RF band edge f_l are converted to a

15   lower band edge $f_{l,IF}$ of the IF band while simultaneously, the RF signal frequency components at the upper RF band edge f_u are converted to an upper band edge $f_{u,IF}$ of the IF band.

A pair of RF frequency bands 'overlaps' if the receiver bandwidth BW is greater than a difference between the center frequencies f_c of the RF frequency bands. For

20   example, if the receiver bandwidth BW is 40 MHz, a first frequency band B_1 having an RF center frequency $f_{c,1}$ equal to 1,000 MHz overlaps a second frequency band B_2 having an RF center frequency $f_{c,2}$ equal to 1,020 MHz. In particular in this example, bands B_1 and B_2 overlap by exactly one-half of the receiver bandwidth BW (i.e., overlap = $BW/2$).

25   In some embodiments, measuring 110 an IF response of the receiver comprises applying an RF stimulus signal $R(f)$ to an input of the receiver, and measuring a response or an IF output signal $I(f)$ of the receiver. Measuring 110 may further comprise computing a transfer function or characteristic for the measurement. The transfer function is a ratio of the measured IF response $I(f)$ over the applied stimulus

30     $R(f)$. In general, the transfer function of the receiver is a complex quantity having a magnitude and phase or equivalently, having a real part and an imaginary part. Thus,

the ratio taken for determining the measured 110 transfer characteristic is a complex ratio.

The RF stimulus signal $R(f)$ is largely a function of a given IF measurement system. In some embodiments, the RF stimulus signal $R(f)$ may be a broadband signal. In some embodiments, the RF stimulus signal $R(f)$ is a periodic broadband signal having a period that is a reciprocal of a measurement frequency resolution Δf. The measurement frequency resolution Δf, in turn, may be chosen such that a step size or tuning resolution of the receiver is an integer multiple of the measurement frequency resolution Δf. The step size or tuning resolution of the receiver is a difference between center frequencies of adjacent bands B or equivalently, a tuning resolution of a local oscillator of a downconversion stage of the receiver. Thus for example, for a receiver having a tuning resolution that is any one of 1.25 MHz, 2.5 MHz or 5 MHz, the measurement frequency resolution Δf may be chosen to be 50 kHz (e.g., 50 kHz x 100 = 5 MHz).

In various embodiments, the broadband signal used as the RF stimulus signal $R(f)$ may include, but is not limited to, a summation of a plurality of sinewaves, a periodic chirped waveform, and a combination thereof. For example, an RF stimulus signal $R(f)$ may comprise a plurality of sinewaves summed together wherein the sinewaves in the plurality are separated in frequency from one another by the measurement frequency resolution Δf. In addition, the sinewaves in the plurality may be each offset in phase from one another in the summation. In some embodiments, the phase offset of the sinewaves is selected to minimize a crest factor of the stimulus signal $R(f)$. Such a phase offset or phase factor for each sinewave in the plurality may be determined by a random search subject to a condition that the crest factor of the summation is minimized, for example. It has been demonstrated that a random search of phase factors may produce a plurality of sinewaves that, when summed, produce a stimulus signal $R(f)$ having a crest factor of approximately 7.85 or less. A crest factor of less than or about 7.85 is acceptably low for many applications of method 100. However, stimulus signals $R(f)$ having higher crest factors may be acceptable in certain situations. Acceptability of a particular crest factor is generally determined on a case-by-case basis for a given measurement system. For example, in some instances acceptability of the crest factor is based on a dynamic range within which the given

measurement system (e.g., as illustrated in Figure 1) is sufficiently linear such that introduced error are negligible with respect to an operational characteristic of the system.

In another example, a constant envelope signal may be employed as the RF

5   stimulus signal $R(f)$. An example of such a constant envelope signal with a low crest factor is a periodic chirped waveform signal. For example, a linear chirped waveform signal may be described in terms of a discrete time variable m as

$$s(m) = \exp(j\theta_m) \qquad m = 1, 2, \cdots, M \qquad (1)$$

where

10
$$\theta_m = 2\pi A(m - C)\frac{m}{f_s} + \theta_0 \qquad (2)$$

and where f_s is a sample frequency and the constants A, C, and θ_0 are selected to satisfy

$$\begin{aligned} \theta_1 &= \theta_M \\ (\theta_2 - \theta_1) &= -2\pi BW_s \\ \theta_0 &= 0 \end{aligned} \qquad (3)$$

in which BW_s is a bandwidth of the chirped waveform signal (e.g., $BW_s \geq$ receiver

15   bandwidth BW).

The crest factor of the real and imaginary components of such a linear chirped waveform signal is that of a pure sinewave (i.e., 3 dB). As such, the linear chirped waveform signal typically requires significantly less dynamic range of a digital-to-analog converter (DAC) used to generate the signal compared to a sum of sinewaves

20   with randomly selected phase factors.

In some embodiments, the bandwidth BW_s of the linear chirped waveform stimulus signal is chosen to be somewhat larger than the receiver bandwidth BW to reduce a deviation that occurs near an upper and lower band edge of the linear chirped waveform stimulus signal. For example, a bandwidth BW_s equal to 6.15 MHz (e.g.,

25   23 percent larger than BW thereby resulting in less than ± 1 dB variation within BW)

may be used to generate such a stimulus signal for use with a receiver bandwidth BW equal to 5 MHz. Employing the linear chirped waveform stimulus signal with a bandwidth BW_s that is larger than the receiver bandwidth BW may result in a magnitude spectrum of the stimulus signal that varies by less than approximately ±1

5 dB within the receiver bandwidth BW.

A maximum value for the discrete time variable m (i.e., M) depends on a particular situation. For example, consider a situation in which the frequency resolution Δf is 50 kHz and a sampling frequency is 56 MHz. A number of frequency samples is then 1,120 and a number of spectral lines produced by the stimulus signal

10 is given approximately by

$$\text{Number of Spectral Lines} \approx \frac{BW_s}{\Delta f} + 1 \tag{4}$$
$$\Rightarrow \text{ For } BW_s = 5 \text{ MHz}, \text{ Number of Spectral Lines} = 101$$

The particular number of frequency samples in the example is a ratio of the sampling frequency and the frequency resolution that equals 1,120. Note that the number of frequency samples 1,120 has factors of 32, 7, and 5. Among other things, this

15 facilitates use of an efficient prime-factor Fast Fourier Transform (FFT) to compute a frequency spectrum thereby minimizing a computational load penalty. For example, having the number of frequency samples equal to 1,120 with factors 32, 7 and 5 allow use of a 4,480-point FFT since such an FFT has factors of 128, 7 and 5. In addition, a period of the stimulus signal equal to a reciprocal of the frequency resolution Δf is 50

20 kHz (i.e., 1/50 kHz = 20 µsec) may be determined along with choosing a sampling period of the stimulus signal of 1/84 µsec. Under such conditions, a maximum value M equal to 1,680 is established (i.e., 20 µsec x 84 µsec^{-1}= 1,680).

Moreover, in certain embodiments a spectral offset of the linear chirped waveform stimulus signal is employed. For example, the spectral offset may be used

25 to avoid or at least reduce measurement errors associated with local oscillator (LO) feedthrough in the signal generator. The spectral offset also may help to avoid or reduce measurement errors associated with images generated by various elements or stages in the signal generator. Stages in the signal generator include, but are not limited to, an IQ modulator. For example, when a linear chirped waveform signal

having spectral lines separated by a frequency resolution Δf of about 50 kHz is employed, a spectral offset of about 12.5 kHz (i.e., $\Delta f/4$) may be used. In such an embodiment, the spectral lines will be located at frequencies given by

$$f_m = f_0 + \left(\tfrac{1}{4} + m\right)\Delta f \quad m = 0, \pm 1, \pm 2, \cdots \tag{5}$$

5   where f_m is a frequency of an mth spectral line and f_0 is carrier frequency (i.e., generally located at the center frequency f_c). An FFT used in processing the measurements obtained from the receiver may have 'frequency bins' located at the frequencies of the spectral lines, for example. As such, the FFT will not be affected by the carrier feedthrough since carrier feedthrough occurs at the carrier frequency f_0.
10   Similarly, the FFT processing will not be affected or hindered by the images since the images occur at frequencies given by

$$f_m = f_0 - \left(\tfrac{1}{4} + m\right)\Delta f \quad m = 0, \pm 1, \pm 2, \cdots \tag{6}$$

Thus, neither the carrier feedthrough nor the images will contribute to measurement errors when using FFT-based processing.

15   In some embodiments, the IF response is measured 110 for bands that overlap by one half of a bandwidth BW. In other words, the IF response is measured 110 for a first band B_1 having center frequency $f_{c,1}$. The receiver is then tuned to a second band B_2 having center frequency $f_{c,2}$ such that $f_{c,2}$ equals $f_{c,1}$ plus $BW/2$. The IF response is measured 110 for the second band B_2. The process of tuning and measuring 110 is
20   repeated for each band B_i. Figure 3 illustrates a graphical representation of an example of a set of measurements plotted as a function of RF frequency for a plurality of overlapping bands according to an embodiment of the invention. The exemplary measurements represent a magnitude of the measured 110 IF frequency response of a receiver under test for several overlapping bands (e.g., B_i where $i = 1, 2, \ldots$). The
25   measurements are indexed by an index k, where individual values of the index k represent discrete frequencies.

Referring again to Figure 2, the method 100 of characterizing an IF frequency response further comprises computing 120 a set of conversion coefficients or weights a_i. The conversion coefficients a_i define a relationship between an actual frequency

response $X(k)$ and the measured frequency responses $Y_i(k)$. The actual frequency response $X(k)$ is the IF response without errors. The conversion coefficient a_i essentially represents a change in an IF conversion loss or response magnitude and an IF phase shift or response phase that occurs in the IF response as a function of tuning or stepping the receiver from one band B_i to a next, overlapping band B_{i+1}. A relationship between the measured frequency responses $Y_i(k)$ and the actual frequency response $X(k)$ is given by

$$Y_i(k) = a_i \cdot X(k) + N_i(k) \qquad (7)$$

where $N_i(k)$ is an introduced error.

In some embodiments, the computed 120 set of conversion coefficients a_i represent an estimate of 'true' or exact conversion coefficients. In such embodiments, the conversion coefficients a_i, more properly denoted $\hat{a}_i$, may be computed or estimated 120 such that the conversion coefficients $\hat{a}_i$ reduce a sum-square difference between the measured 110 overlapping frequency responses for the bands. In some embodiments the estimated 120 conversion coefficients $\hat{a}_i$ minimize the sum-square difference. For simplicity herein and not by way of limitation, distinction between the estimated conversion coefficients, $\hat{a}_i$ and the 'true' conversion coefficients is made only where such a distinction is necessary for a proper understanding. Otherwise the estimated and true conversion coefficients are considered interchangeable and the same notation, namely 'a_i', is used to denote both herein.

To continue, consider an exemplary set of IF frequency response measurements $Y_i(k)$ illustrated in Figure 3 where an index variable i corresponds to an ith band of the measured 110 IF response. A plurality of related subgraphs are illustrated in Figure 3, one subgraph for each of three exemplary bands B_i. The index k indexes discrete frequency response measurement points within each of the bands B_i as indicated in Figure 3 where the index k is plotted along respective x-axes while an amplitude of the response measurement $Y_i(k)$ is plotted with respect to respective y-axes of the subgraphs. Also in Figure 3, the center frequency $f_{c,i}$ of each of the bands B_i is respresented by a center point on respective x-axes of each of the subgraphs.

As illustrated in Figure 3, there are $2N+1$ discrete frequency points measured in each band B_i, where N is an integer (e.g., $N = 5$). Thus, k ranges from $-N$ to N and k equals 0 at the center frequency $f_{c,1}$ for band B_1. For band B_2, k ranges from 0 to $2N$ and k equals N at the center frequency $f_{c,2}$. In band B_3, k ranges from N to $3N$ with k equaling $2N$ at the center frequency $f_{c,3}$, and so on.

A set of half-band measurements $Z_i(k)$ may be defined in terms of the exemplary set of measurements $Y_i(k)$ for overlapped band portions as

$$Z_1(k) = Y_1(k) \quad k = 0, 1, \cdots, (N-1)$$
$$Z_2(k) = Y_2(k) \quad k = 0, 1, \cdots, (N-1)$$

and for $i = 2, 3, \cdots$ \hfill (8)

$$Z_{2i-1}(k) = Y_i(k) \qquad k = (i-1)N, (i-1)N + 1, \cdots, iN - 1$$
$$Z_{2i}(k) = Y_{i+1}(k) \qquad k = (i-1)N, (i-1)N + 1, \cdots, iN - 1$$

Having defined the half-band measurements $Z_i(k)$ according to equation (8), the conversion coefficients a_i are defined in terms of another coefficient b_i with a first conversion coefficient a_1 arbitrarily set to 1, as given by equation (9), namely

$$a_{i+1} = b_i \cdot a_i; \quad i = 1, 2, \cdots \quad \text{and } a_1 = 1 \hfill (9)$$

In some embodiments, the other coefficient b_i is estimated or determined in terms of the half-band measurements $Z_i(k)$ as

$$b_i = \frac{\sum\limits_{k=0}^{N-1} Z_{2i}[k + N(i-1)] \cdot Z_{2i-1}^*[k + N(i-1)]}{\sum\limits_{k=0}^{N-1} |Z_{2i-1}[k + N(i-1)]|^2} \quad i = 1, 2, 3, \cdots \hfill (10a)$$

where Z_{2i-1}^* is the complex conjugate of Z_{2i-1}.

In other embodiments, the other coefficient b_i is estimated or determined by averaging the half-band measurements $Z_i(k)$ in the overlapping half bands. For example, the other coefficient b_i may be given in terms of the half-band measurements $Z_i(k)$ as simply

$$b_i = \frac{1}{N} \sum_{k=0}^{N-1} \frac{Z_{2i}[k + N(i-1)]}{Z_{2i-1}[k + N(i-1)]} \qquad i = 1, 2, 3, \cdots \qquad (10b)$$

Referring again to Figure 2, the method 100 of characterizing an IF frequency response further comprises determining 130 an estimate of the actual frequency response $\hat{X}(k)$. The estimated frequency response $\hat{X}(k)$ is determined as a weighted average of the measured 110 IF response wherein estimates of the conversion coefficients a_i are employed as weights. In some embodiments, estimates of the set of conversion coefficients a_i are used in conjunction with the half-band measurements $Z_i(k)$ to determine the estimated frequency response $\hat{X}(k)$ as given by

$$\hat{X}[k + (i-1)N] = \frac{1}{2} \left\{ \frac{1}{a_{2i}} Z_{2i}[k + (i-1)N] + \frac{1}{a_{2i-1}} Z_{2i-1}[k + (i-1)N] \right\};$$

$$\text{for} \begin{cases} k = 0, 1, 2, \cdots, N-1 \\ i = 1, 2, 3, \cdots \end{cases} \qquad (11)$$

Thus, the conversion coefficients a_i are computed 120 from the other coefficient b_i using equation (9) wherein the other coefficient b_i is found or estimated by employing either equation (10a) or equation (10b) along with the measured 110 IF response converted using equation (8) to half-band measurements $Z_i(k)$. An average, such as that given by equation (11), is then used to determine 130 the estimated frequency response $\hat{X}(k)$.

In some situations, a delay misalignment among the frequency samples in the IF response measurements may interfere with the method 100. In particular, if timing errors occur between one or more of the IF response measurements, a delay misalignment may be present. Such delay misalignment often manifests itself as a random added delay in the overlapping measurements.

Therefore, in some embodiments, the method 100 may be modified to reduce the effects of such a delay misalignment. As such, some embodiments of the method 100 further comprise removing a delay misalignment from either the set of IF frequency response measurements $Y_i(k)$ or the half-band IF frequency response

measurements $Z_i(k)$ at overlapping frequency bands prior to computing 120 the conversion coefficients a_i.

In such embodiments, removing the delay misalignment comprises finding a phase progression in a ratio of measurements from overlapping bands. Removing the delay misalignment further comprises multiplying the measurement ratios by a complex conjugate of the phase progression to remove the phase progression. Following removal of the phase progression, the ratios may be employed to compute the other variable b_i and then the conversion coefficient a_i as detailed hereinabove. In some of these embodiments, a linear regression is used to find the phase progression.

For example, the phase progression P may be found by computing a set of ratios indexed on k of half-band measurements $Z_{2i}(k)/Z_{2i-1}(k)$ for a pair of overlapping bands. More than one set of ratios for more than one overlapping band may be computed. Phase values p_k of each ratio of the set of ratios may be determined by taking the angle (i.e., angle($\cdot$)) of each ratio in the set.

The phase values p_k may be normalized by removing a typical phase amount from the phase values p_k. For example, to normalize the phase values p_k, a middle phase value p_{mid} may be subtracted from each phase value p_k. The middle phase value p_{mid} may be a phase value for a ratio approximately halfway between a lower end and an upper end of a half-band, for example.

A linear regression is then employed to find the phase progression P across the overlapping band. Essentially, the linear regression determines a best-fit straight line through the normalized phase values p_k. The best-fit straight line is a phase slope or phase progression P that 'best fits' the normalized phase values p_k. The notion of 'best fit' herein is used in a conventional sense to mean that a deviation or difference between data and a line or curve representing the data is minimized according some metric. An example of a linear regression that may be employed is given by

$$P = \frac{N\sum_k k \cdot p_k - \left(\sum_k k\right)\sum_k p_k}{N\sum_k k^2 - \left(\sum_k k\right)^2} \qquad (12)$$

Once the phase progression P is found by using, for example, equation (12), the phase progression P may be removed from the measurements prior to computing 120 the conversion coefficients a_i. For example, the phase progression P may be subtracted from the phase of each of the ratios $Z_{2i}(k)/Z_{2i\text{-}1}(k)$ prior to computing the other coefficient b_i using equation (10b). Subtracting the phase progression P essentially multiplies the ratios $Z_{2i}(k)/Z_{2i\text{-}1}(k)$ by a complex conjugate of the phase progression P.

In some embodiments, the method 100 of characterizing an IF frequency response optionally further comprises removing 140 an RF tilt. An RF tilt may be introduced by a tilt or slope in a magnitude response of an RF filter in the measurement system, for example. The RF tilt produces a corresponding error in the magnitude of the estimated IF frequency response.

In some embodiments, removing 140 the RF tilt comprises measuring 110 an IF response of the receiver, computing 120 a set of conversion coefficients, and determining 130 an estimate of the estimated IF frequency response $\hat{X}(k)$ for each of an IF response $X(f)$ and an image of the IF response $X_{image}(f)$. In other words, measuring 110, computing 120, and determining 130 are first performed with a first receiver LO setting to produce the IF response $X(f)$. The receiver LO is then adjusted such that an image IF response $X_{image}(f)$ is generated. Then measuring 110, computing 120, and determining 130 are repeated for the image IF response $X_{image}(f)$.

For example, the first receiver LO setting may be such that the LO is at a first frequency $f_{LO,1}$ that is below an RF center frequency f_c of the RF band B. Such an LO setting produces an IF response $X(f)$ having a center frequency $f_{c,IF}$ (e.g., $f_{c,IF} = f_c - f_{LO,1}$ for $f_{LO,1} < f_c$). An IF response $X(f)$ produced by an LO setting with the first frequency $f_{LO,1}$ less than the RF center frequency f_c is sometimes referred to as a 'lower sideband' IF response. The image IF response $X_{image}(f)$ for this example is then generated by setting the LO to a second frequency $f_{LO,2}$ that is correspondingly above the RF center frequency f_c of the RF band B (e.g., $f_{c,IF} = f_{LO,2} - f_c$ for $f_{LO,2} > f_c$). Such an image IF response $X_{image}(f)$ may be referred to as an 'upper sideband' IF response.

Thus, for removing 140 an RF tilt, measuring 110, computing 120, and determining 130 are repeated for each of the upper and lower sideband IF responses

$X(k)$, $X_{image}(k)$, to produce a pair of estimated IF responses $\hat{X}(k)$, $\hat{X}_{image}(k)$. The estimated IF response $\hat{X}(k)$ and the estimated image IF response $\hat{X}_{image}(k)$ have RF tilts with opposite signs or slopes.

Removing 140 the RF tilt further comprises combining the estimated IF
5   response $\hat{X}(k)$ and the estimated image IF response $\hat{X}_{image}(k)$. In some embodiments, combining comprises computing a square-root of a product of the estimated IF response $\hat{X}(k)$ and the estimated image IF response $\hat{X}_{image}(k)$. The RF tilt is essentially cancelled or eliminated from the combined estimated IF response as a result of the opposite slopes of the estimated IF response $\hat{X}(k)$ and the estimated
10   image IF response $\hat{X}_{image}(k)$.

Figure 4 illustrates an IF measurement system 200 according to an embodiment of the present invention. The IF measurement system 200 characterizes an IF response of a receiver 201 under test that is connected to the system 200. The IF measurement system 200 characterizes the IF response such that an effect on the
15   characterization of errors associated with uncertainties in knowledge of an RF stimulus signal $R(f)$ (i.e., 'stimulus uncertainty') used to perform the characterization is reduced. In some embodiments, the system 200 characterizes the IF response such that the effect of the stimulus uncertainty is minimized. In some embodiments, the system 200 essentially implements the method 100 of characterizing an IF frequency
20   response of a receiver described hereinabove.

The IF measurement system 200 comprises a signal generator 210. The signal generator 210 generates an RF stimulus signal $R(f)$ that is applied to an input of the receiver 201 under test. The generated RF stimulus signal $R(f)$ is described hereinabove.

25   In some embodiments, the signal generator 210 comprises a baseband stimulus source, a transmitter baseband filter, an upconverter, and a transmitter RF filter. For example, the signal generator 210 may be essentially the upconverting transmitter 10 illustrated in Figure 1. The baseband stimulus source produces a baseband stimulus signal $S(f)$. The stimulus signal $S(f)$ passes through and is filtered by the baseband

filter having a transfer function $H_g(f)$. A filtered baseband signal $G(f)$ is produced at an output of the baseband filter. The filtered baseband signal $G(f)$ is upconverted to an RF signal having an RF frequency by the upconverter. The upconverter includes a tunable local oscillator (LO), a tuning of which determines the carrier frequency of

5   the RF signal. The RF signal is then passes through and is filtered by the transmitter RF filter to produce the RF stimulus signal $R(f)$. In other embodiments, an RF stimulus source directly generates (i.e., without frequency converting a baseband signal) the RF stimulus signal $R(f)$. Any of a variety of signal generators known in the art may be employed as the signal generator 210.

10   The IF measurement system 200 further comprises an IF processor 220. The IF processor 220 receives an IF output signal $I(f)$ produced by the receiver 201 under test. The IF processor 220 comprises an analog-to-digital converter (ADC) to convert the IF output signal $I(f)$ into a digitized IF response. In some embodiments, the IF processor 220 may further comprise analog and/or digital filtering that may be applied

15   to one or both of the IF output signal $I(f)$ prior to digitizing and the digitized IF response.

The IF measurement system 200 further comprises a controller 230. In some embodiments, the controller 230 is a general-purpose computer such as, but not limited to, a personal computer (PC) or a computer workstation. In other

20   embodiments, the controller 230 is a specialized processing engine or processing element of the IF measurement system 200 including, but not limited to an embedded microprocessor and an embedded microcomputer. The controller 230 receives and processes the digitized IF response from the IF processor 220. In addition, the controller 230 may provide timing information and tuning control to the signal

25   generator 210 and the receiver 201 under test as well as may provide control to the IF processor 220.

The IF measurement system 200 further comprises a computer program 240 stored in a computer readable form in a memory of the controller 230. The computer program 240 may further or alternatively be stored in a computer readable media that

30   may be read by the controller 230.

The computer program 240 comprises instructions that implement characterizing an IF response of the receiver 201 under test. Specifically, instructions

of the computer program 240 implement characterizing the IF response such that an effect on the characterization by errors associated with uncertainties in knowledge of the RF stimulus signal $R(f)$ (i.e., 'stimulus uncertainty') used to perform the characterization is reduced or in some embodiments, is minimized. In some

5   embodiments, the instructions of the computer program 240 implement determining an estimate of an actual IF response of the receiver from IF responses of the receiver under test measured for overlapping frequency bands, the estimate being determined from a set of overlapping frequency response measurements weighted by the estimated values of the conversion coefficients.

10   In some embodiments, the instructions of the computer program 240 essentially implement the method 100 of characterizing an IF frequency response described hereinabove. In addition, instructions of the computer program 240 may further implement controlling the tuning and timing of the signal generator 210, tuning of the receiver 201 under test, and controlling the IF processor 220.

15   In some embodiments, instructions of the computer program 240 implement measuring an IF response of the receiver, computing a set of conversion coefficients from the measured IF response, and determining an estimate of an actual IF frequency response $\hat{X}(k)$ using the measured IF response and estimates of the conversion coefficients. In some embodiments, measuring an IF response may be essentially

20   measuring 110 described hereinabove with respect to the method 100. Similarly, computing the set of conversion coefficients and determining the estimated IF frequency response $\hat{X}(k)$ may be essentially computing 120 and determining 130 of the method 100, respectively. The instructions of the computer program 240 optionally further comprise removing an RF tilt. In some embodiments, removing an

25   RF tilt may be essentially removing 140 described hereinabove with respect to the method 100.

Thus, there has been described various embodiments of the present invention that facilitate characterizing an IF response of a receiver such that effects of stimulus uncertainties with respect to a RF stimulus signal are reduced or may be minimized.

30   It should be understood that the above-described embodiments are merely illustrative of some of the many specific embodiments that represent the principles of the present

invention. Those skilled in the art can readily devise numerous other arrangements without departing from the scope of the present invention.